UCRL- 92439
PREPRINT

EXPERIMENTAL LEVEL-STRUCTURE DETERMINATION IN ODD-ODD ACTINIDE NUCLEI

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This document was prepared for presentation as an invited paper at the 35th National Conference on Nuclear Spectroscopy and Structure of Atomic Nuclei, Leningrad, USSR
April 16-19, 1985

April 4, 1985

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EXPERIMENTAL LEVEL-STRUCTURE DETERMINATION IN ODD-ODD ACTINIDE NUCLEI*

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ABSTRACT

The status of experimental determination of level structure in odd-odd actinide nuclei is reviewed. A technique for modeling quasiparticle excitation energies and rotational parameters in odd-odd deformed nuclei is applied to actinide species where new experimental data have been obtained by use of neutron-capture gamma-ray spectroscopy. The input parameters required for the calculation are derived from empirical data on single-particle excitations in neighboring odd-mass nuclei. Calculated configuration-specific values for the Gallagher-Moszkowski splittings are used. Calculated and experimental level structures for ^{238}Np, ^{244}Am, and ^{250}Bk are compared, as well as those for several nuclei in the rare-earth region. The agreement for the actinide species is excellent, with bandhead energies deviating 22 keV and rotational parameters 5%, on the average. Applications of this modeling technique are discussed.

* Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

The study of nuclear level structure in the actinide element region has progressed rather slowly over the past few decades, relative to comparable studies in regions of lighter elements. Contributing factors include the difficulty of producing and handling of these species and the presence of interfering radiations due to both inherent and induced radioactivities, the latter arising, for example, from the fission process. Although there have been several reviews of actinide level structure published, a more notable recent effort being that for odd-mass nuclei by Chasman et al.[1], none have treated odd-odd structure in any depth.

The most important development in the experimental study of odd-odd actinide nuclei in the past eight years or so has been the advent of high resolution, high sensitivity spectrometers for measuring the radiations accompanying the neutron capture reaction. Prior to their introduction, knowledge of odd-odd actinide structure had been obtained from study of alpha and beta decay leading to nuclei such as ^{238}Np, ^{246}Am, ^{248}Bk, and ^{250}Bk. Generally, this work lead to the identification of, at most, 20-25 levels in a given nucleus, and the observation of perhaps as many gamma ray transitions.

If one considers only those odd-odd nuclei that can be studied via the neutron capture reaction, there are potentially only six cases in the actinide region where sufficient long-lived target material can be obtained for use in the measurements. The status of structure determination for five of these nuclei is reported in Table 1. Although, in principle, ^{228}Ac can be studied also, no measurements have been reported; the difficulties in handling 22-year ^{227}Ac target material, even in microgram quantities, has precluded its use in this application.

It can be seen in Table 1 that all of the listed nuclides have been measured using neutron-capture gamma-ray spectrometry at the Institut Laue-Langevin. Another very important experimental technique has been the measurement of gamma rays following average resonance capture(ARC) with 2- and

Table 1. Recent experimental determinations of nuclear structure for selected odd-odd actinide nuclei.

Nucleus	Technique	Laboratory	Reference[a]
232Pa	(n,γ)thermal	ILL[b]	Boerner, Schreckenbach measurement 1983
238Np	(n,γ)thermal	FRI[c]	Ionescu, Nucl. Phys. A313, 283(1979)
	(n,γ)thermal	ILL[b]	Kern, measurement 1978
	(n,γ)ARC	BNL[d]	Hoff, measurement 1982
	α decay	LLNL[e]	Hoff, measurement 1978
	(d,p)	ANL[f]	Ionescu, Nucl. Phys. A313, 283(1979)
242Am	(n,γ)thermal	FRI[g]	Kern, footnote g
	(n,γ)thermal	ILL[b]	Kern, measurement 1982
	(d,p)	NBI[h]	Grotdal, Phys. Scr. 14, 263(1976)
244Am	(n,γ)thermal	ILL[b]	von Egidy, Phys. Rev. C 29, 1243(1984)
	(d,p)	NBI[h]	Grotdal, Phys. Scr. 14, 263(1976)
250Bk	(n,γ)thermal	ILL[b]	Hoff, footnote i
	(d,p)	PU[j]	Hoff, footnote i
	α decay	ANL[k]	Koenig, Bull. Am. Phys. Soc. 27, 532(1982).

a - For published references, only the first author's name is listed.

b - Institut Laue-Langevin, Grenoble. Measurements with curved crystal gamma-ray diffraction spectrometers(GAMS) and electromagnetic conversion-electron spectrometer(BILL).

c - University of Fribourg. Measurement with Ge(Li) detectors in pair and anti-Compton spectrometers using reactor SAPHIR in Wuerenlingen.

d - Brookhaven National Laboratory. Average resonance capture(ARC) measurement with 2-keV neutrons.

e - Lawrence Livermore National Laboratory, California. Gamma-gamma coincidence measurement.

f - Argonne National Laboratory, Chicago. Measurement with 12-MeV deuterons from tandem accelerator and split-pole magnetic spectrograph.

g- M. Gasser and J. Kern, U. Fribourg report IPF-SP-008 (1977).

h - Niels Bohr Institute, Copenhagen. Measurement with 12-MeV deuterons from tandem accelerator and single-gap spectrograph.

i - R. W. Hoff et al., Capture Gamma-Ray Spectroscopy and Related Topics-1984,Ed. S. Raman, American Institute of Physics Conference Proceedings Series, No. 125, p.274 (1985).

j - Princeton University, New Jersey. Measurement with 20-MeV deuterons from cyclotron and Q3D spectrometer.

k - Argonne National Laboratory, Chicago. Alpha, gamma, and conversion electron measurements; singles and coincidence.

24-keV filtered neutron beams at the Brookhaven National Laboratory. Although ^{238}Np is the only nucleus in Table 1 that has been investigated so far using the ARC technique, it is anticipated that it will be feasible to employ both ^{241}Am and ^{243}Am targets in future experiments. Finally, an important aspect of structure determination is the use of several complementary experimental probes. For the nuclei in Table 1, alpha decay and single-nucleon transfer-reaction measurements have provided important information regarding specific orbital assignments for the unpaired nucleons in the residual nuclei.

It is clear from both experimental studies and theoretical concepts that the level structure of an odd-odd deformed nucleus is extremely complex. Compared with an odd-mass nucleus, there are at least two factors that lead to greater level density at a given energy: 1) The presence of a second unpaired nucleon, and 2) The possibility for coupling the angular momenta of these unpaired nucleons in two ways, either parallel or anti-parallel. The effect of these is to increase the level density at moderately low excitation energies by a factor of 4, compared with the average for odd-mass species at the same energy. Thus, experimental data for odd-odd species can be very complex and their interpretation becomes challenging. For example, the GAMS/BILL measurements[2] for ^{244}Am produced evidence for 775 transitions in the energy range 0-1400 keV. In such cases, it is very helpful to have a model on which to base the interpretation of experimental data. Using the model described in this paper, it became possible to place 300 of the observed transitions in a level scheme for ^{244}Am.

The method used in this paper to model the level structure of odd-odd deformed nuclei is based upon a technique first described in papers by Struble, Motz, et al.[3] and Scharff-Goldhaber et al.[4] They proposed that if the p-n residual interaction energy is small compared with the energy with which the odd nucleons are bound to the core, the excitation can be calculated by a simple extension of the odd-A model and the interaction energy can be treated later as a perturbation. Thus, the model can be described in terms of two simple concepts. The first is that in considering the coupling of two unpaired particles to a deformed core, the excitation energy of a given configuration can be described as the sum of each of the odd-nucleon excitations. The second concept is that the effective moment of inertia for a rotational band can be expressed as the sum of three components: the moment of inertia of the even-even core plus increments from the addition of each of the two odd nucleons.

The excitation of an odd nucleon in a deformed nucleus can be treated theoretically by various versions of single-particle potential theory. For the purposes of this paper, however, the excitations are obtained from experimental data for neighboring odd-mass nuclei. The quasiparticle energy E_{qp} for a given orbital in an odd-mass nucleus can be found from the expression

$$E_I = E_{qp} + \hbar^2/2\theta[I(I+1)-K^2+\delta_{K,1/2}\, a(I+1/2)(-1)^{I+1/2}] \, , \qquad (1)$$

where a is the decoupling parameter. One merely needs an experimental energy for the bandhead level (for which $E_I = E_K$), and the quasiparticle energy for the orbital can be obtained from Eq. 1.

The effective moment of inertia for a given rotational band, , is derived by the following method:

$$\begin{aligned}
\theta_{\text{odd-odd}} &= \theta_{\text{even-even}} + \delta\theta_p + \delta\theta_n \\
&= \theta_{e\text{-}e} + (\theta_p - \theta_{e\text{-}e}) + (\theta_n - \theta_{e\text{-}e}) \\
&= \theta_p + \theta_n - \theta_{e\text{-}e}. \qquad (2)
\end{aligned}$$

where θ_p and θ_n are the moments of inertia for the relevant rotational band in the neighboring odd mass nuclei and $\delta\theta_p$ and $\delta\theta_n$ are the increments to the value of $\theta_{\text{even-even}}$ due to the unpaired proton and neutron. In the model being discussed here, effects due to Coriolis mixing that are peculiar to odd-odd nuclei are not included. However, those experimentally-observed manifestations of Coriolis mixing in odd-A nuclei such as the compression or expansion of rotational spacing within a given band are included in the calculated effective moment of inertia for the odd-odd nucleus.

The excitation energies of levels in the odd-odd nucleus are calculated using the expression

$$E_I = E^p{}_{qp} + E^n{}_{qp} + h^2/2\theta_{odd\text{-}odd}[I(I+1)-K^2]$$

$$- (1/2-\delta_{\Sigma,0})E_{GM} - {}_{K,0}(-1)^I E_N \pi, \qquad (3)$$

where π denotes the parity of the states and is equal to ± 1 for positive or negative parity.

The E_{GM} and E_N terms in Eq. 3, which are designated as the Gallagher-Moszkowski splitting[5] and Newby shift,[6] respectively, are functions of the effective neutron-proton residual interaction. For the actinide elements, Gallagher-Moszkowski splittings and Newby shifts have been calculated[7] recently assuming a zero-range central (δ) force between proton and neutron and a Nilsson-type potential. The one adjustable parameter needed to describe the strength of the force is obtained from a global fit of G-M splittings in the actinide region, specifically the experimental values for the 12 configuration pairs shown in Figure 1. Calculated and experimental E_{GM} and E_N values are listed in Table 2.

Several authors have published calculations of G-M splittings and Newby shifts made assuming simple central forces.[8] Boisson et al.[9] have worked with empirical data from rare-earth nuclei involving an initial sample of E_{GM} matrix elements for 43 two-quasiparticle configurations that was reduced to 23 empirical values of greatest reliability. They determined parameters for several forms of an assumed central-force effective interaction by fitting the calculated matrix elements to the empirical data. Sood and Singh[10] have calculated E_{GM} matrix elements for configuration pairs in the nuclei ^{238}Np, ^{244}Am, and ^{250}Bk with a zero-range proton-neutron residual interaction. For the adjustable parameter that determines the strength of the interaction, they have chosen to adopt a different value for each nucleus; the value is usually adjusted to reproduce the G-M splitting that includes the ground state rotational band. For the 9 G-M splittings in these nuclei where comparison can be made with experiment, their calculations show approximately the same level of agreement as for those listed in Table 2.

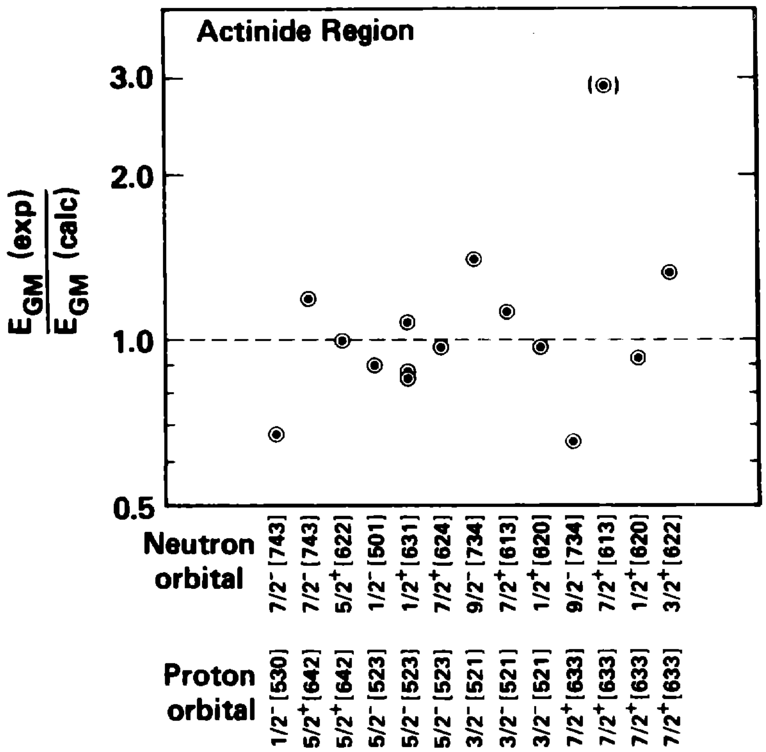

Figure 1. Comparison of experimental and calculated Gallagher-Moszkowski matrix elements for several configuration pairs in odd-odd actinide nuclei.

A comparison between the experimental and calculated bandhead energies and rotational parameters of ^{244}Am is given in Table 3. The calculated level energies, which have been obtained using Eq. 3, were given a zero-energy adjustment so that the calculated and experimental ground state energies match. The experimental data for ^{244}Am include information from recent measurements using the (n,γ) and (d,p) reactions.[2] The information on the level schemes of neighboring nuclei was taken largely from the Table of Isotopes.[11] The uncertainties on bandhead energy listed in the fourth column of Table 3 do not represent experimental error, but rather are derived from the spread in the experimental values taken from the odd-mass nuclei. The agreement between experimental and calculated bandhead energies for ^{244}Am is excellent; the average deviation is $\pm$19 keV. Similarly, the experimental rotational parameters agree extremely well with the calculated values; the average deviation is $\pm$7%.

Table 2. Comparison of experimental and calculated E_{GM} and E_N values for configurations in some actinide nuclei.

Proton Config.	Neutron Config.	Nucleus	E(GM/N)[a] (keV) Exp.	Calc.	Exp/Calc
1/2⁻[530]	7/2⁻[743]	234Pa	77.5	117.	0.67
	1/2⁺[631]	234Pa	N-46.8	-44.2	1.06
		236Pa	N-50.2	-44.2	1.14
		238Np	N-37.9	-43.1	0.88
5/2⁺[642]	1/2⁺[631]	238Np	82.4	70.	1.18
5/2⁻[523]	1/2⁻[501]	242Am	39.	44.	0.89
	1/2⁺[631]	238Np	52.2	60.	0.87
		242Am	52.1	61.	0.85
		244Am	70.	61.	1.15
	1/2⁺[620]	242Am	21.	116.	0.18
		244Am	16.	116.	0.14
	5/2⁺[622]	238Np	1.	95.	0.01
		240Am	10.	96.	0.10
		242Am	5.	96.	0.05
		238Np	N+27.	-15.2	-1.78
		240Am	N+28.	-14.7	-1.90
		242Am	N+27.3	-14.6	-1.87
		244Am	N+25.7	-14.6	-1.76
	7/2⁺[624]	244Am	200.2	208.	0.96
3/2⁻[521]	9/2⁻[734]	248Bk	186.5	134.	1.39
	7/2⁺[613]	250Bk	66.4	60.	1.11
	1/2⁺[620]	250Bk	110.3	115.	0.96
7/2⁺[633]	7/2⁺[624]	244Am	N+33.1		
	9/2⁻[734]	248Bk	122.	189.	0.65
	7/2⁺[613]	250Bk	135.0	47.	2.87
		250Bk	N-25.0	-58.0	0.43
	1/2⁺[620]	250Bk	83.1	60.	1.39
	3/2⁺[622]	250Bk	91.2	69.	1.32
	1/2⁻[761]	250Bk	38.		

a - The values listed below are Gallagher-Moszkowski matrix elements except when indicated as a Newby term by an N in col. 4.

In Table 4 comparisons are summarized for three actinide nuclei where new experimental data have been obtained, ^{238}Np, ^{250}Bk, and ^{244}Am, and for several rare-earth nuclides. As already noted for ^{244}Am, the agreement for the actinide species is excellent, with bandhead energies deviating 22 keV and rotational parameters 5%, on the average. Corresponding deviations for the five rare-earth nuclei are 47 keV and 7%. As an illustration of the power of using empirical data obtained from neighboring odd-mass nuclei, a calculation was made with theoretical quasiparticle excitations for the odd-nucleons in ^{238}Np taken from Nilsson potential calculations.[12] The average deviation (experimental minus calculated) for the 9 bandhead energies in ^{238}Np was 163 keV; this can be compared with an average deviation of 29 keV obtained using empirical quasiparticle excitations. Similar differences are expected for the other nuclei listed in Table 4.

Table 3. Comparison of experimental and predicted band-head energies and rotational parameters for ^{244}Am.

K	Configuration	Bandhead Energy Exp. (keV)	Bandhead Energy Calc. (keV)	Rot. Par. A Exp. (keV)	Rot. Par. A Calc. (keV)
1^+	$5/2^+[642]p - 7/2^+[624]n$	85	60 ± 42	3.4	3.0
1^-	$5/2^-[523]p - 7/2^+[624]n$	173	161 ± 14	5.3	5.4
2^-	$3/2^-[521]p - 7/2^+[624]n$	259	235 ± 56	5.8	5.8
0^-	$5/2^-[523]p - 5/2^+[622]n$	$286(1^-)$	$319 \pm 31(1^-)$	5.3	5.4
3^+	$1/2^+[400]p - 7/2^+[624]n$	345	(336)	5.2	(5.4)
0^+	$7/2^+[633]p - 7/2^+[624]n$	$374(0^+)$	$362 \pm 69(0^+)$	6.0	6.9
2^+	$5/2^+[642]p - 1/2^+[631]n$	(416)	451 ± 56	(2.7)	3.1
2^+	$5/2^-[523]p - 9/2^-[734]n$	417	426 ± 21	4.1	4.2
3^-	$5/2^-[523]p + 1/2^+[631]n$	418	442 ± 28	(5.6)	5.7
0^+	$5/2^+[642]p - 5/2^+[622]n$	$(475)(2^+)$	$463 \pm 59(2^+)$	--	3.0
2^-	$5/2^-[523]p - 1/2^+[631]n$	482	488 ± 28	(6.6)	5.7
2^-	$5/2^+[642]p - 9/2^-[734]n$	514	538 ± 49	3.2	2.6
2^+	$3/2^+[651]p - 7/2^+[624]n$	(612)	(395)	(5.8)	(6.2)
1^+	$5/2^-[523]p - 7/2^-[743]n$	(668)	665 ± 14	--	5.8
1^-	$3/2^-[521]p - 5/2^+[622]n$	678	586 ± 74	5.1	5.7
1^-	$5/2^+[642]p - 7/2^-[743]n$		826 ± 42		3.1
Average deviations:		19 (for 9 bands)		0.28(7.4%) (for 9 bands)	

Table 4. Odd-odd nuclei in actinide and rare-earth regions: Comparison of experimental and calculated bandhead energies, rotational parameters, and G-M splittings.

Nucleus	Number of bands	Energy range (keV)	$\langle E_{exp}-E_{calc}\rangle$ (keV)	$\langle A_{exp}-A_{calc}\rangle$ (keV)	E_{GM} exp/calc
^{238}Np	9	0 - 345	29	0.14 (3.2%)	1.18,0.87
^{244}Am	16	0 - 680	19	0.28 (7.4%)	1.15,0.14,0.96
^{250}Bk	14	0 - 570	17	0.20 (4.7%)	1.11,0.96,2.87, 1.39,1.32
^{160}Tb	8	0 - 380	41	0.61 (8.1%)	1.03,1.07,1.13
^{166}Ho	10	0 - 560	47	0.74 (8.7%)	0.80,1.08,1.31
^{170}Tm	5	0 - 450	63	0.46 (5.2%)	2.04,0.98
^{176}Lu	12	0 - 840	58	1.0 (9.2%)	1.14,0.48,1.01, 0.91,0.39
^{182}Ta	7	0 - 270	24	0.47 (3.9%)	0.94,0.97,1.14

Thus, the evidence shows this modeling technique accurately reproduces experimental band-head energies and rotational parameters for these deformed nuclei. With this method, then, one can model all of the intrinsic single-particle excitations and rotational bands built on these excitations in any deformed odd-odd species where input data are available. This includes a capability to model structure in some odd-odd nuclei for which little or no experimental data exist; the modeling technique requires no specific knowledge of structure in the odd-odd nucleus of interest, other than calculated matrix elements arising from the proton-neutron interaction. Calculated level schemes can be extended to energies somewhat higher than the ranges given in Table 4, although it must be recognized that other kinds of excitations in these nuclei, e.g., vibrational motion and quasiparticle excitations involving more than two unpaired nuclei, are neglected in this limited approach.

Several applications of this modeling technique have proven to be useful. For example, an average resonance capture measurement[13] populating levels in

^{176}Lu has been performed using the filtered neutron beams available at the Brookhaven High Flux Beam Reactor. A comparison of the cumulative number of levels obtained from the experiment with a corresponding calculated set, a total of 40 predicted rotational bands, shows that they are generally in good agreement. Another example of application of the model involves the calculation of cross-section ratios for the production of isomers in neutron-induced reactions, both capture and (n,2n), where the product nuclei are odd-odd deformed species. It has been found that the hundreds of discrete levels and their gamma-ray branching ratios provided by the modeling are necessary in order to achieve agreement between calculation and experiment.[14]

It is a pleasure to thank H.G. Boerner, J.P. Boisson, R.F. Casten, T. von Egidy, D.G. Gardner, M.A. Gardner, J. Kern, R. Piepenbring, K. Schreckenbach, D.D. Warner, and D.H. White for many stimulating discussions, active assistance, and permission to quote unpublished experimental data. The author wishes to thank G.L. Struble and R.G. Lanier for providing a computer code used to calculate some of the matrix elements listed in Table 1. The support of C. Gatrousis in this work is gratefully acknowledged.

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